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CANADARM: 20 YEARS OF MISSION SUCCESS THROUGH ADAPTATION

Michael Hiltz, Craig Rice, Keith Boyle and Ronald Allison
MacDonald Dettwiler Space and Advanced Robotics Ltd.
9445 Airport Road Brampton ON L6S 4J3
&
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center Houston, Texas, 77058
mhiltz@mdrobotics.ca crice@mdrobotics.ca kboyle@mdrobotics.ca & ronald.l.allison1@jsc.nasa.gov

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Abstract

As part of the National Aeronautics and Space Administration's Space Shuttle Transportation System, the Shuttle Remote Manipulator System has played a vital role in the success of over 60 space missions. This paper examines the enhancements made to the arm to improve its operational capabilities, reduce risk and extend its life. This paper concludes that the robustness and success of the Canadarm over its 20 year life can be attributed to the adaptations that have been made to it to meet the increasing demands that have been placed on the system. Potential future enhancements based on operational trends are also discussed.

1 Introduction

The Shuttle Remote Manipulator System (SRMS, a.k.a the Canadarm) flew its inaugural flight onboard the Space Shuttle Columbia (STS-2) in November of 1981. The four arms that are in service today as part of NASA's Space Shuttle fleet have enjoyed 20 years of successful use over 60 missions. Although it shares common mechanical elements with its original design, the SRMS is significantly different than it was 20 years ago. Mission success over its operational life has been achieved by making constant adaptations to the Canadarm. These changes have been based on the experience of the hardware performance in the environment of space as well as addressing new operational requirements. Since 1981 the arms have undergone numerous hardware changes, improvements in manufacturing processes and over 39 changes to the control software.

In making adaptations to the arm, three key items have been, and continue to be, addressed:

1.) Expanding the system's capabilities.
2.) Reducing risk through improvements in safety.
3.) Improving the arm's ability to meet the flight manifest (supportability).

The purpose of this paper is to examine how the SRMS has been improved to address lessons learned from the prolonged use of robotics in space. This paper will also discuss trends in the operational use of the arm and how they relate to past, current and future upgrade activities.

2 Canadarm Adaptations to Expand Operational Capability

2.1 Original Operational Requirements: Payload Deployment and Retrieval

The original arm was designed primarily for the deployment and retrieval of payloads and is part of the Shuttle's Payload Deployment and Retrieval System (PDRS). It was designed to capture "free-flying" payloads fitted with a grapple fixture and manoeuvre them for both berthing (in the cargo bay) and deploying. The arm was originally designed to manoeuvre with unloaded tip speeds of 2 ft/sec and 2 deg/sec yet be able to precisely control payloads up to 65,000 lbm.

2.2 Operational Evolution of Canadarm: Common Uses

Although originally designed for payload deployment and retrieval, over the years the SRMS has proven very useful for a wide variety of other mission critical tasks. In addition to deployment and retrieval of payloads current use of the arm regularly includes such vital tasks as:

a) Assembling Space Stations: The arm was used to help install a docking module on the Russian MIR space station in November of 1995. The arm has become essential in the assembly of the International Space Station (ISS) having assembled approximately 100 tons of ISS hardware to date.

b) Workhorse for Spacewalks: Using different types of foot restraints attached to the end of the arm, the arm has provided a mobile and stable work platform for Extra Vehicular Activities (EVA). This allows the spacewalking astronauts to accomplish a greater variety of tasks in a shorter period time. In conjunction with the EVA crew, relatively large payloads can be moved about the cargo bay for repair and assembly operations.

c) Flying "eye-in-the-sky" for visual inspection of the Orbiter and payloads: The arm elbow camera with a pan and tilt unit and an arm tip camera mounted on the wrist roll joint have been instrumental in troubleshooting many on orbit anomalies.

   The arm and its cameras are commonly used to observe the functions of other Orbiter subsystems and troubleshoot Orbiter thermal protection system deterioration. The arm has also been used to view cargo bay debris jarred loose from launch, jammed EVA hatch doors and view ice that has frozen to the Orbiter.

d) Portable light source: Lighting mounted on the end of the arm is used to provide extra illumination for both direct window viewing and camera inspection and grapple tasks.

e) Use for Public Relations activities: In addition to providing vital video cues to the crew for performing operational tasks, cameras on the arm and mounted in payloads attached to the arm (such as IMAX cameras) have been used to bring the experience of space to the general public.

f) Experimental platform for Materials: To study the effect of micrometeorite debris on various materials the arm has been fitted numerous times with a witness plate near the wrist joint.

2.3 Operational Evolution of Canadarm: Unique Tasks

In addition to the now common tasks, the arm has also been used for a variety of unique tasks. Examples of these include:

a) "Fly-swatter / lacrosse stick" to activate a satellite's separation switch; After the Syncom failure on STS-51D, a "flyswatter/ lacrosse stick" (fashioned from the binder of an operations checklist) was attached to the end of the arm and used to activate Syncom's separation switch.

b) Ice-pick to knock ice off the Orbiter to prevent damage during re-entry of the shuttle (on STS-41D).

c) Use of the arm's end effector as a sunshade for astronomy observations (STS-85; Southwest Ultraviolet Imaging System).

d) "Pushing" on jammed antenna: The arm was used to assist stowing of the stuck SIR-B antenna on STS-41G.

e) Experimental platform for Orbiter plume characterisation tests. (SPIFEX).

f) Contingency operations in support of payload materials experiments; The Wake Shield Facility (WSF) experimental platform was designed to generate an ultra-vacuum environment to support Molecular Beam Epitaxy (MBE) growth of semi-conductor films. On its inaugural flight an anomaly with Wakeshield's attitude control systems occurred that prevented its release. The arm was used to hold WSF away from the Orbiter cargo bay to avoid debris and allow completion of mission objectives.

2.4 Canadarm Operational Trends

As the importance and versatility of the Canadarm became more evident over the life of the Orbiter, an increased engineering emphasis on expanding and improving existing capabilities emerged. New operational requirements, driven in large part by ISS assembly tasks, requires the arm to perform more challenging tasks that had not been envisioned when it was originally designed. ISS assembly tasks involve connecting large mass payloads with a variety of interface attachment systems. The interfaces between ISS elements are designed by a diverse assortment of subcontractors (including several international partners) and are significantly different than the those used in the shuttle's cargo bay which were designed for regular payload deployment and retrieval.

As a result of past and planned ISS assembly tasks there has been an explicit focus on the following capabilities and features of the arm:

a) Ability to manoeuvre larger mass payloads with large centre of mass offsets (including a fully assembled Space Station),
b) Accurate trajectory control,
c) Precise (finer) control at low rates,
d) Positioning accuracy,
e) Force capabilities,
f) Ability to backdrive arm,
g) Displaying more data to the operator,
h) More flexibility in command and display capabilities

2.5 Expanding Canadarm System Capabilities

While some of the Canadarm tasks have been within the inherent capabilities of the original design, many new tasks have been accomplished through modifications to the arm. The following is a list of adaptations made to the arm to address operational trends (discussed in 2.4) that have either provided new functionality or improved existing capabilities. These enhancements to the arm capabilities now allow these new tasks to be routinely performed.

2.5.1 Joint Controller Upgrades

One of the biggest challenges of the original Canadarm servo design was the requirement to manoeuvre a wide range of payload masses over a considerable range of rates. The ability to quickly move the tip of an unloaded arm at 2 ft/sec and 2 deg/sec and yet still be able to manoeuvre a 65,000 lbm payload was accomplished in the original design using only one set of servo control parameters in the joint's analog Servo Power Amplifiers (SPAs). To meet the new requirement to manoeuvre a fully assembled Space Station (up to 586,000 lbm), a redesign of the arm's SPAs was undertaken. A digital SPA design was developed that would allow the arm operator to select (via software) different sets of servo parameters depending on whether the payload was above or below 65,000 lbm. In addition to allowing the arm to manoeuvre Space Station sized payloads, the digital SPAs were also designed to provide the arm with more accurate trajectory control and provide more precise control at low rates.

The accuracy of the arm's trajectory relative to the operator commands is governed by the ability of the six joints to quickly accelerate and accurately match corresponding individual joint rate commands issued by the arm control systems. Any small differences in the co-ordination, sequencing and response between the individual joint rates leads to errors in the operator desired trajectory. To improve arm trajectory accuracy two methods of correction have been employed. One that corrects for joint rate errors at the servo (the source of the error) and another which superimposes corrections to the operators commands based on trajectory error (system response to the error). Ensuring accurate joint rate performance at the servo level was addressed by the digital SPA redesign while corrections made at the systems level were addressed by the addition of Position Orientation Hold Select (POHS) software changes discussed in 2.5.2.

An inherent characteristic of the original analog servo system was that at low motor currents (which corresponded with low joint and tip rates) a non-linearity existed in the output of the Motor Drive Amplifier (MDA) in the SPA (see Figure 1). This resulted in less precise control of payloads at very low rates. This is a particular concern when manoeuvring large mass payloads such as the ISS. With the design of the digital SPA this non-linearity has been eliminated resulting in consistent servo performance throughout the operational range of the MDA.

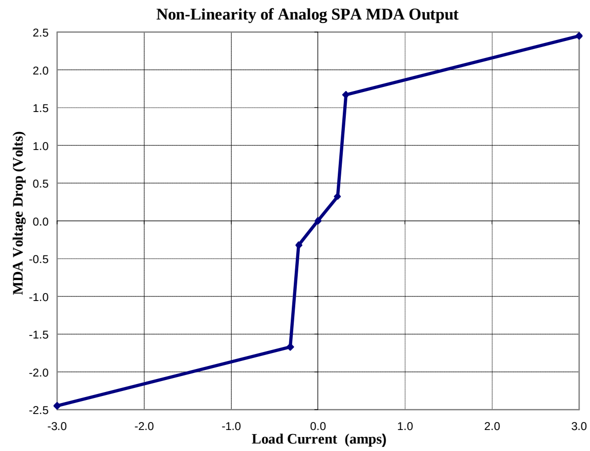

Figure 1 Analog SPA MDA Performance [1]

The digital SPA design also incorporated a new feed forward function that improved rate tracking across the entire range of joint rates. The improvements in trajectory control that were realised with the digital SPA are illustrated in a simulation shown in Figure 2. With a 180K payload, significant deviation from the desired trajectory would be seen by the operator. With the close tolerance interfaces that are involved with Space Station assembly this type of deviation would be unacceptable.

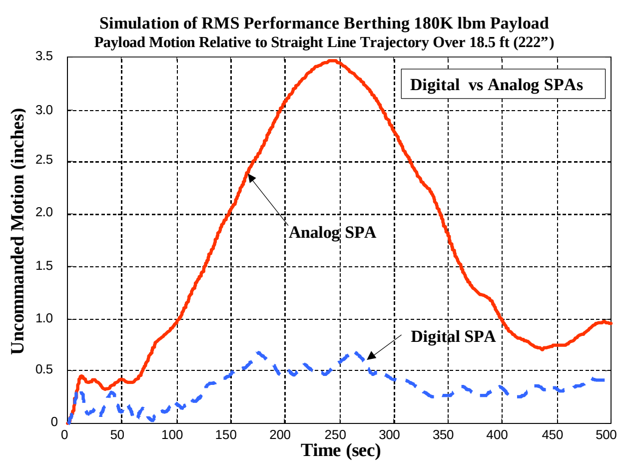

Figure 2 SPA Trajectory Tracking Performance [1]

2.5.2 Control Software Modifications

While improvements in trajectory accuracy were achieved in the re-design of the servos, significant additional improvement to arm trajectory tracking has also been realised through the introduction of a

Position Orientation Hold Select (POHS). POHS is a new control software feature that superimposes corrections to the operator commands based on the overall system response. POHS compensates for any Canadarm trajectory errors (uncommanded motion) by altering the operator commands internally within the control software. Figure 3 illustrates an example of trajectory improvements that were realized as a result of the incorporation of POHS.

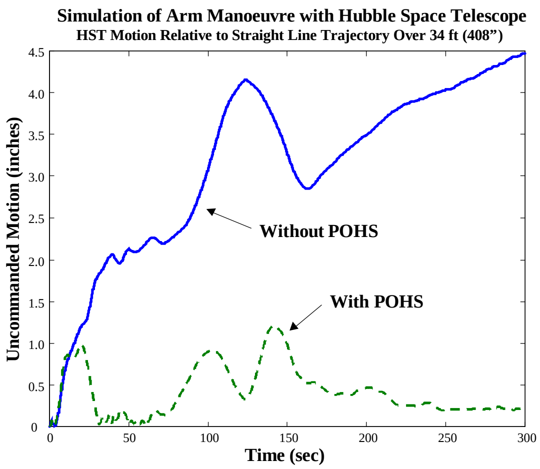

Figure 3 POHS Trajectory Tracking Performance

Greater flexibility was introduced to the display and control capabilities of the Canadarm. New features were added that would allow the arm operator to display arm positioning data relative to any user defined referenced frame. Additionally, new methods of command (referred to as "Fly-to/Fly-from") were added which allowed the operator to choose which command reference frame they preferred. These features were added, in large part, to address the preferences of arm operators. Many of the Canadarm operators come from the Air Force or have backgrounds as pilots and, as such, this new feature made manoeuvring payloads with the arm more intuitive. Based on a camera view fixed to the Orbiter or the payload attached to the arm during berthing operations, the operators can now select their desired command frame as though their reference frame were at this interface.

Numerous software modifications have also been made over the life of the arms to display additional operational data and arm status information on the Orbiter's General Purpose Computer (GPC) SPEC displays. The software was also changed to allow overrides and switch re-assignments to provide workarounds for various failure scenarios.

2.5.3 End Effector Redesign

A major redesign of the arm's end effector was implemented to upgrade its capabilities. To improve the payload-to-end effector interface stiffness the rigidization load with which the arm "pulls" on the grapple fixture was increased from 740 lb_f (min) /800 lb_f (nom) to 900 lb_f (min)/ 1100 lb_f (nom). This significantly increased the loads required to generate any interface separation and enabled the arm to manoeuvre higher mass payloads.

2.5.4 Operational Techniques Based on Knowledge of System

In addition to addressing new operational challenges with hardware upgrades as previously discussed, engineers have developed operational techniques to expand system capabilities based on 20 years of flight experience and characterisation of actual system performance. As the complexity of the tasks that the arm was required to perform increased with the ISS assembly operations there has been an intensified focus placed on the positioning accuracy capabilities of the arm. While many of the tasks requiring fine alignment of the arm's payload have been accomplished with the aid of a visual cue system (most notably the Space Vision System) there has been an increased reliance on the accuracy of the arm's display of position and attitude data as complementary information.

Arm position and attitude information is computed from encoders on each of the six joints (precision of 0.0055 deg). The specified accuracy of the arm position and orientation at the End Effector is ±2 inches (3-sigma) and ±1 degree (3-sigma) respectively, relative to the Orbiter reference frame whose origin is at the base of the arm. This accuracy specification, by itself, it is not particularly useful when assessing the accuracy of predicted payload positions (fixed with respect to the Orbiter) for operations planning. All sources of potential error (in addition to any arm errors) must be considered when assessing the pre-flight predicted position and orientation accuracy. As part of an effort to understand past performance, translational and rotational errors were calculated for 91 fixed payload grappled configurations up to STS-97 (using predicted vs actual arm configuration; 87 in Orbiter cargo bay, 4 on ISS). This method takes into account all sources of potential error. Table 1 contains a summary of this overall positioning error data.

Orbiter Ref.	Max Error	Mean (n=91)	1 Sigma
X	-1.3 in (LDEF)	-0.1 in	+/- 0.5 in
Y	2.7 in (Z1-ISS)	-0.2 in	+/- 0.7 in
Z	-1.6 in (SPARTAN 207)	-0.2 in	+/- 0.6 in
RSS	**2.8 in (Z1-ISS)**	**1.0 in**	+/- 0.5 in
P	-0.7 deg (CRISTA-SPAS)	-0.1 deg	+/- 0.2 deg
Y	-0.8 deg (SPARTAN-201)	0.0 deg	+/- 0.2 deg
R	-0.7 deg (WSF-2)	0.0 deg	+/- 0.3 deg
Total Angle	**0.9 deg (SPARTAN 51G)**	**0.4 deg**	+/- 0.2 deg

Table 1 SRMS Predicted vs Actual Positioning Errors [1]

As can be seen in Table 1 the mean translational and rotational errors are well within the +/-2 inches and +/- 1 deg arm accuracy specification. However, since these values include all sources of error (not just the arm) the actual arm accuracy is likely much better than this. It has been found that in general the predicted versus actual position errors during ISS assembly are greater than those of payloads in the cargo bay. This can be attributed to the greater number of interfaces and potential sources of error that are associated with ISS assembly operations. As such, caution is exercised when referencing encoder based position data for ISS operations. However, the encoder based rotational data has been found to be an acceptable operator reference cue for ISS assembly.

To improve on the use of arm encoder based translational position data to augment other visual cue systems during ISS assembly operations an on-orbit calibration technique was developed. By using the predicted vs actual errors from an ISS fixed payload grapple performed prior to attaching an ISS element, a re-calibrated predicted position can be determined and used as a reference. This technique was used successfully on STS-102 to help relocate Pressurised Mating Adapter 3 on the Unity Node.

Although the Canadarm was designed as a rate controlled system, its ability to exert force has become a more common requirement for assembly tasks. The ability of the arm to exert a force poses unique challenges for the arm. When the operator issues a rate command to manoeuvre the arm (or attached payload) along a particular trajectory corresponding joint rate commands are issued to the servos to achieve this rate. With contact and the application of force the joint torques increase to try and achieve the operator desired rate, however, the sum of the different joint torques rarely equates to a force in the desired direction. The force capability of the arm is highly dependent on arm configuration, arm rate limits and the geometry of the contact area. Furthermore, any trajectory deviations as a result of "sliding" due to contact also results in POHS issuing rate commands to maintain the desired trajectory.

For the majority of ISS assembly operations the force capabilities of the arm meets the requirements of the various ISS elements and their interfaces. Successful installation of the ISS elements where the arm has been required to exert force has been achieved by thorough pre-mission planning and training to obtain precise alignment of the two elements being attached, prudent selection and use of arm rates and employing specific command techniques.

Force capabilities are a particular concern when performing assembly operations where the force requirements are near the limit of the arm's capabilities. On STS-74 the assembly of the Russian Docking Module (DM) to the Orbiter Docking System (ODS) posed a unique set of challenges for the arm. The force requirements at the DM to ODS interface (known as the Androgynous Peripheral Docking System (APDS)) were found to be within the arm's capabilities when both elements were aligned very precisely. However, any misalignment between the two elements substantially increased the force required to mate the two. A technique was developed to position the DM above the ODS, limp the arm and then initiate the Orbiter's thrusters for a 1 second pulse. The inertia of the DM and arm were used to effectively allow the Orbiter to dock to the DM with sufficient force to guarantee capture. This method was successfully used on STS-74 and also used twice on STS-88 to assemble the first two ISS elements.

2.5.5 Development of PC Card

To provide more operational data to the arm operator a PC card was developed to provide a data interface directly from the arm's Manipulator Controller Interface Unit (MCIU). The MCIU controls the flow of data between the Display & Control panel, the Orbiter's GPC and the arm itself. By providing a PC card interface to the MCIU a laptop can be used to display more real time operational data.

2.5.6 Canadarm Add-ons

The Canadarm has been modified numerous times to incorporate additional cameras in support of robotic operations. Side-view and RF cameras have been added to the wrist roll joint to provide additional camera views. Additionally, an EVA camera connector has been added to the end effector numerous times and used by spacewalking astronauts to provide camera views (including closeout photos) to the ground.

A mounting bracket that was added as part of the end effector redesign has also been used to mount materials science and shuttle plume experiments. Also in support of materials science experiments the lower boom of the Canadarm has been fitted with a witness plate containing various materials to assess the effect of exposure to the environment of space.

3 Improving Safety and Reducing Risk

While safety has always been of paramount importance in the design and build of hardware used in manned spaceflight programs, the Challenger accident in 1986 created re-emphasis on increasing safety and reducing risk. Following the accident, a concerted effort to re-assess all hardware to identify any possible areas of improvement in safety was undertaken. All Canadarm systems were re-visited and scrutinised using Failure Modes and Effects Analysis (FMEA) to ensure that all precautions had been taken to reduce risk.

The primary safety concern associated with the use of the RMS on-orbit is avoiding collisions between the arm or attached payloads and Orbiter structure or EVA crew. Under worst case conditions collisions could cause a Loss of Life or Vehicle which is the most critical safety issue. In normal operations, the RMS operator has the primary responsibility for collision avoidance between the arm, any payloads and Orbiter structure.

The risk associated with collision avoidance is minimized through extensive pre-flight planning to ensure satisfactory clearance between Orbiter structure and the arm or attached payloads during arm operations. Collision avoidance during on-orbit operations is aided with the use of direct window and camera views and RMS operational data on the D&C Panel.

With certain arm failure modes the risk of a potential collision is higher. Joint runaways, sluggish, frozen or free joints, uncommanded release and uncommanded de-rigidization failures of the end effector are, in the worst case, failure modes that are most associated with causing an unintended collision. Another important concern associated with on-orbit use of the arm is the inability to drive the arm. Under worst case conditions a loss of arm drive could cause a Loss of Mission which is a critical issue. Loss of arm drive is associated with worst case sluggish, free, or frozen joint, failure modes.

Throughout the life of the Canadarm an extensive effort has gone into implementing hardware and software safety features to detect and handle any possible RMS failures. In addition, preventative on-orbit procedures are used to help catch and avoid any conditions that could pose a potential safety concern. Furthermore, extensive generic and mission specific workaround procedures are developed to address any possible contingencies.

After the intensive post Challenger re-examination of Canadarm safety issues a number of new precautions were taken operationally, new software features were added and many of the critical failure modes were eliminated or mitigated by design in subsequent system upgrades. The following is a list of the most significant changes made to improve safety.

3.1 Built-In Test Hardware

The redesign of the arm's joint controllers (SPAs), to support space station assembly tasks, presented the opportunity to implement safety upgrades along side performance upgrades. The digital SPAs resulted in a safer system by eliminating all of the critical single point failure modes (21 Crit 1/1s) from the original analog design. This was accomplished through the introduction of extensive built-in test hardware to monitor critical functions of the SPA and to respond in a fail-safe manner when a failure condition is detected.

Similarly, the redesign of the arm's manipulator controller interface unit (MCIU) has eliminated all 8 single point critical failure modes. The MCIU is responsible for the transfer of critical command and status information between the operator's workstation, the shuttle's general purpose computer and the arm itself. As such, corruption of this data has potentially catastrophic results. Single point failure modes were eliminated through the implementation of redundancy and fail-safe circuit design. This included redundant processing of the operator's hand controller commands, continuous monitoring of communication buses and the replacement of active autosafing with fail-safe autobraking.

3.2 Software Health Monitoring

A brake slip check algorithm was added to the arm's control software to detect and annunciate a slip in the individual joints of 0.5 deg or a total slip in all six joints of 2.0 degrees while the brakes are on.

With the introduction of POHS, the trajectory error relative to the operator desired command was computed within the control software. This error was used to provide an additional safety check to ensure that arm motion stayed within a safe boundary. This new software feature, referred to as Trajectory Tracking and Error Detection, ensures arm stays within 8 inches and 3 degrees of the operator desired trajectory. If the arm deviates from this envelope the brakes of the arm are automatically applied and an alarm is annunciated.

A software feature to detect joint runaways at low rates was also implemented to reduce risk when operating the arm. The Vernier Consistency Check implemented in the control software compares the commanded joint rates to the actual joint rates and ensures that they are within a pre-defined tolerance.

If the joint rate exceeds an acceptable level the brakes of the arm are automatically applied and an alarm is annunciated.

3.3 Operational Procedures and Flight Rules

Generic and mission specific procedures and flight rules, which govern how the operator is to use the arm on-orbit, play an important role in reducing risk. Based on system capabilities and potential failure modes identified in the FMEA activity operations procedures and flight rules incorporate a number of operational constraints which ensures that arm performs its tasks in as safe a manner as possible. Arm procedures and flight rules address such issues as proximity operations, arm velocity, mode availability, available viewing and thermal constraints. Many of these procedures and rules have been adapted to incorporate knowledge of past and current system capabilities.

4 Improving Ability to Meet the Flight Manifest - Supportability

The Canadarm was designed for a service life of 10 years and 100 missions. Today, 20 years into its service life, NASA's fleet of arms has flown a total of just over 60 missions. With NASA planning to continue Shuttle flights until 2012 and possibly 2020, a structured maintenance and refurbishment plan is required to ensure continued success. Supportability focuses on combating obsolescence, ensuring spares availability and reducing repair cycle time in the event of hardware failures.

Similar to NASA's scheduled Orbiter Maintenance Down Period (OMDP), a program of component inspection, refurbishment and replacement has been implemented for the Canadarm. Maintenance and upgrades are consolidated to avoid the costs of piecemeal refurbishment. Replacement electronic, electromechanical and active sub-assemblies are fit, form and functionally compatible with the components they replace. This ensures flexibility and eliminates costs and logistical difficulties associated with mixed-fleet operations.

Logistics planning has established the level and quantities of spares dependent on predicted failure rates and estimated repair cycle times. For example, due to the mechanical complexity of the end effector and the potential for an extended repair cycle, five (5) complete end effectors were put into service supporting the fleet of four (4) arms. Components such as brakes, motors and commutators are assembled into motor modules, tested and spared as completed assemblies ready to be fitted to an arm if required.

Hardware wear-and-tear, long-term effects of exposure to the thermal and vacuum environments of space, obsolescence and supportability risks are addressed through established inspection and maintenance requirements and prudent redesign and upgrade programs.

Very little of the Canadarm hardware has remained untouched. Within the last 10 years 90% of the arm-based electronics has been redesigned including the elimination of two electronic boxes by consolidating functionality within redesigned units. Gearboxes have been disassembled, inspected and re-lubricated. Structural components such as the carbon composite boom segments have been inspected via ultrasonic, x-ray and visual methods to verify continued flight worthiness.

End effectors were upgraded in the early 1990's incorporating numerous changes to improve reliability and life. These changes included:

a) Selected gears surface hardened by nitriding.
b) Mechanism damping and energy absorbing devices added to lessen mechanism impact loads.
c) Motor winding impregnation material changed to improve heat dissipation.
d) Brakes and clutch torque ratings increased to increase life and provide redundancy.

Redesigned brake units providing improved long term wear and friction performance characteristics are replacing the original brake units.

Although outwardly today's Canadarm is indistinguishable from the arm which first flew in 1981, it is a very different arm. A structured program of maintenance, inspection and replacement is ensuring continued success for the next 20 years of service.

5 Potential Future Upgrades

Based on operational trends and task requirements in previous missions, several potential upgrades to the Canadarm have been identified. These include:

a) Incorporation of a Force Moment Sensor (FMS) at the end of the arm: The present SRMS design does not provide a means of determining tip force information for either the control system or operator display. In situations where the payload is misaligned with respect to the berthing guides, the operator must manually adjust the rate commands to overcome the effect of contact forces in order to accomplish a berthing task. This becomes a more difficult task if the operator does not have sufficient information from visual cues to provide adequate situational awareness. Using the Force Moment Sensor data a Force Moment Accommodation (FMA) feature can be designed to automatically modify rate commands to alleviate forces and moments at the tip of the arm. This would nullify the effect of contact forces. This force control capability can be used to help align a payload within the interface alignment guides during the mating of space station components. FMA can therefore facilitate berthing tasks where the mating interface is obscured from operator view making visual alignment difficult. An FMA/FMS design for the Special Purpose Dexterous Manipulator (SPDM) has been tested at MDR using the SPDM GT (Ground Testbed) with an operator-in-the-loop. The test results showed that FMA significantly eased the operator workload leading to a reduction in task timelines.

FMA could also be help to counteract constrained forces thereby limiting the build-up of loads within the SRMS. An example where FMA would have been beneficial occurred on STS-88 during the retraction of the APDS interface to mate the Russian Functional Cargo Block (FGB) to the Node. The forces required to backdrive the electrically limp (full motor current attenuation) arm joints were high enough to cause a misalignment between the two elements. An FMA design could have employed active limping and ensured that the arm imparted no force during the retraction.

b) Display and Control Panel: While most of the major components of the SRMS system have been upgraded or redesigned, the main operator interface to control the arm remains as it was originally built. The current display and control panel is limited to three digital displays and elector-mechanical barberpole, meters and switches. A new display and control panel could consolidate all arm command and display capabilities into one location. In addition to increased operational flexibility, improvements in safety could be realised through improved operator situational awareness and the elimination of the 16 single point failure modes that currently exist.

c) Incorporation of Strain Gauges along the arm: Life load estimates for the arm have been based on estimated launch and landing loads. To ensure that the arm can continue to meet its launch manifest for another 20 years the actual load cycles that the arm undergoes during each launch and landing is required. Mounting strain gauges that are powered on during launch and landing would provide an accurate assessment of the stresses that the arm has undergone and provide a better estimate of remaining life.

6 Concluding Remarks

The Canadarm has been highly successful over its 20 years of use aboard the Space Shuttle. Although the original build of the arm met all of its original design requirements, continued success and improvements in safety (reduced risk) have been ensured through prudent upgrades to the system. These adaptations were based on knowledge (or lessons learned) from prolonged operation in the environment of space and adapting to new operational requirements. On-going and future adaptations to the arm will ensure that the Canadarm is able to continue to meet its scheduled launch manifest until 2020.

References

[1] The contents of this paper are original. However, the material denoted [1] was previously prepared by the authors as part of RMS sustaining engineering analysis for the National Aeronautics and Space Administration and can be found in the SRMS Jeeves database.

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